Determination of the Radio Transmitter Coordinates In Satellite Communication Systems

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***Abstract* — The method to determine the coordinates of the radio transmitter, which is located outside the Earth's surface, using the virtual antenna array, is described in this article. Variations of the calculation method, based on the construction of the pyramid, are considered. The errors of this method are given.**

Keywords — satellite communication system, determination of the coordinates, virtual antenna array, radio source, radio transmitter.

I. INTRODUCTION

The modern world can not be imagined without satellite technology. Satellite communication systems are widely used in television, telephony, geolocation, etc. Usually satellite communication systems consist of spacecraft used as retranslators and terrestrial or near-Earth transceivers.

Due to the availability of these systems, there may be cases of illegitimate use of spacecraft's frequency resources. [1-3] The various methods based on determining the origin of the radio transmitter are a promising direction in this area. [4-7].

II. EXISTING METHODS BASED ON THE USE OF THE VIRTUAL ANTENNA ARRAY

A. Radio Transmitter Is Located on the Earth's Surface

The method based on the use of the virtual antenna array (further — VAA) is known. Geostationary artificial satellite is not static while the coordinates of its position are known at each instant. Using several sequent satellite positions forms the virtual antenna array. The coordinates of the RT can be determined by measuring the phase difference between the signals emitted by them in these positions of the satellite. [6-7] However, this method does not allow to determine the coordinates of the RT in case if it is unknown whether the RT is located on the Earth's surface or outside it.

B. Method Based on the Use of Cons

Therefore it is proposed to use an improved variation of the method based on the use of the VAA, which allows to determine the coordinates of the RT which is located outside the Earth's surface.

The method based on the use of cones is described in the paper [7]. With high accuracy it can be assumed that emitting of the antenna on board of the satellite forms in space a circular conical surface, the apex of which is the subsatellite point. Displacement of the satellite leads to the second cone and the associated local coordinate system. The RT is located at the intersection of three conical surfaces. To determine its location, it is necessary to solve a system of equations:

$$\left.\begin{aligned} n_1^1x^2+n_2^1y^2+n_3^1z^2+m_1^1\,xy+m_2^1yz+m_3^1xz+p_1^1x+p_2^1y+p_3^1z+q_1^1+q_2^1+q_3^1=0 \\ n_1^2x^2+n_2^2y^2+n_3^2z^2+m_1^2\,xy+m_2^2yz+m_3^2xz+p_1^2x+p_2^2y+p_3^2z+q_1^2+q_2^2+q_3^2=0 \\ n_1^1x^3+n_2^1y^3+n_3^1z^3+m_1^3\,xy+m_2^3yz+m_3^3xz+p_1^3x+p_2^3y+p_3^3z+q_1^3+q_2^3+q_3^3=0 \end{aligned}\right\} \quad (1)$$

where $n_j^i, m_j^i, p_j^i, q_j^i$ are known numeric coefficients. [8].

III. METHOD BASED ON THE USE OF THE PYRAMID

However, the disadvantage of the described method is that the solution of such a second-order system of equations requires a lot of computing power. Therefore a simpler way to calculate the coordinates of the RT, which is located outside the Earth's surface, was developed — a method based on the use of the pyramid.

Generally, points A_1, A_2, A_3 and B (where the RT is located) define a pyramid wherein the triangle $A_1A_2A_3$ is its base and the point B is its apex as it is shown in Fig. 1.

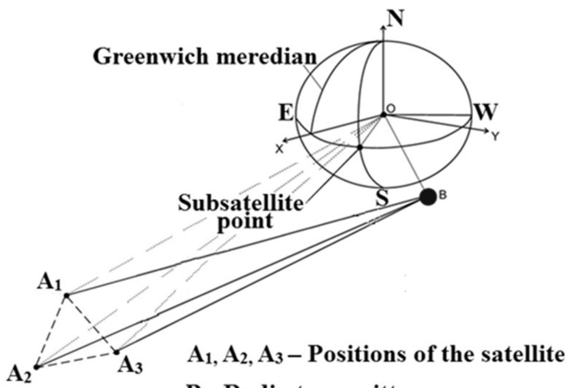

Fig. 1 – General geometrical constructions for the method to determine the radio transmitter coordinates based on the use of the pyramid

Depending on the relative position of the point B and the base of the pyramid, two cases can be distinguished:

A. Location of the radio transmitter can be projected on the base of the pyramid

If the RT is located relatively to the satellite so that projection of the point B on a plane, which is defined by three positions of the satellite (points A_1, A_2, A_3), is in the limits of the triangle $A_1A_2A_3$, it is expedient to use the following method to determine the RT coordinates.

Define an auxiliary rectangular Cartesian coordinate system (CS) with an origin at the point A_1; A_1A_2 is OX; the axis OZ is parallel to the height BO, lowered from the point B on the base of the pyramid; the axis OY is perpendicular to axes OX and OZ (Fig. 2).

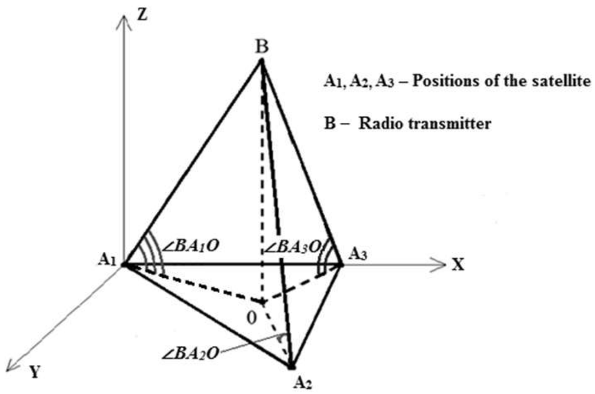

Fig. 2 – An auxiliary coordinate system for the method of determining the radio transmitter coordinates based on the use of the pyramid

In the geocentric CS, points A_1, A_2, A_3 have following coordinates (satellite ephemeris): $A_1(x_1;y_1;z_1)$, $A_2(x_2;y_2;z_2)$ and $A_3(x_3;y_3;z_3)$.

Determine the angles in the base of the pyramid:

$$\angle BA_1O = \frac{\pi}{2} - \frac{\psi_1}{2},$$
$$\angle BA_2O = \frac{\pi}{2} - \frac{\psi_2}{2},$$
$$\angle BA_3O = \frac{\pi}{2} - \frac{\psi_3}{2}, \tag{2}$$

where ψ_1, ψ_2, ψ_3 are the angles of the axial section of the conical surfaces.

Knowing the side lengths of the base of the pyramid (it follows from the fact that coordinates of the points A_1, A_2, A_3 are known) and the angles (2), we are able to calculate the coordinates of the point B in the auxiliary CS. To calculate the RT coordinates in the geocentric CS, we must execute the axis rotation of the auxiliary CS and its parallel transport.

B. Location of the radio transmitter cannot be projected on the base of the pyramid

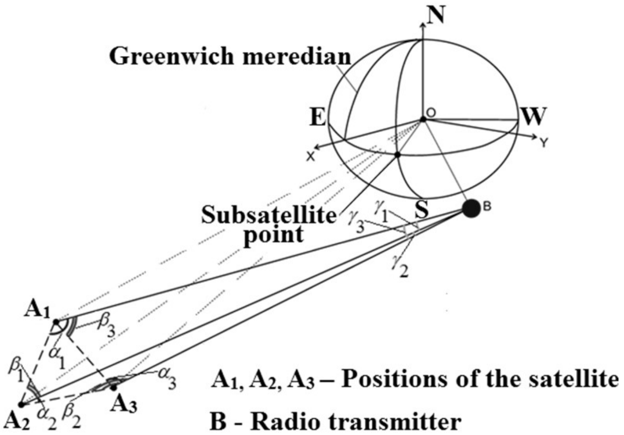

Fig. 3 – Geometric constructions for the method of determining the radio transmitter coordinates based on the use of the pyramid

The angles in the bases of each of the faces of the pyramid are determined based on the phase difference of the incoming signal at the points A_1, A_2, A_3:

$$\alpha_i = \arccos\left(\frac{\lambda}{2\pi d_i} \cdot \Delta\psi_{ij}\right),$$
$$\beta_i = \arccos\left(\frac{\lambda}{2\pi d_i} \cdot \Delta\psi_{ji}\right), \tag{3}$$

where di is the ith base of VAA,

$\Delta\psi_{ij}$ is the phase difference of the incoming signal to the adjacent points. [9]

Knowing these angles and the coordinates of the points in base of the pyramid, we are able to build a system of equations based on the Law of Sines:

$$\sqrt{(x_2 - x_B)^2 + (y_2 - y_B)^2 + (z_2 - z_B)^2} \cdot \sin\gamma_1 = \sin\alpha_1 \cdot A_1A_2,$$
$$\sqrt{(x_3 - x_B)^2 + (y_3 - y_B)^2 + (z_3 - z_B)^2} \cdot \sin\gamma_2 = \sin\alpha_2 \cdot A_2A_3, \tag{3}$$
$$\sqrt{(x_1 - x_B)^2 + (y_1 - y_B)^2 + (z_1 - z_B)^2} \cdot \sin\gamma_3 = \sin\alpha_3 \cdot A_3A_1,$$

where x_1, y_1, z_1 are the coordinates of the point A_1,

x_2, y_2, z_2 are the coordinates of the point A_2,

x_3, y_3, z_3 are the coordinates of the point A_3,

x_B, y_B, z_B are the coordinates of the point B.

To calculate the coordinates of the point B, i.e. the RT coordinates, we must solve this system.

Comparing the two above-described methods, we come to the following conclusions: the first method is simpler mathematically, but is suitable for a limited number of cases.

The second method is more general, however, the calculations are more complex.

IV. Errors of the Method Based on the Use of the Pyramid

Ones of the main sources of errors are the inaccuracies of the satellite ephemerides prediction and the error of the phase difference measurement.

A. Impact of the inaccuracies of the satellite ephemerides prediction

There are a complex dependences between the errors of determining the RT coordinates and the inaccuracies of the satellite ephemerides prediction. When changing the satellite ephemerides prediction inaccuracy from 0 to 100 m by the ephemeris X_2, resultant error of determining the RT coordinates ranges from 5 to 50 m as it is shown in Fig. 4. [10].

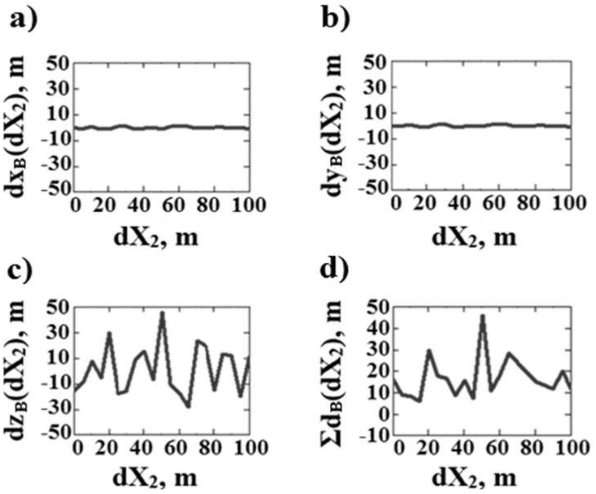

Fig. 4 – Dependences between the errors of determining the radio transmitter coordinates and the inaccuracy of the satellite ephemeris prediction, dX_2, at the point A_2 of the virtual antenna array:

a – Error of determining the radio transmitter coordinate x_B
b – Error of determining the radio transmitter coordinate y_B
c – Error of determining the radio transmitter coordinate z_B
d – Resultant error of determining the radio transmitter coordinates

Plots of dependences between the errors of determining the RT coordinates and the inaccuracies of the satellite ephemerides prediction by the ephemerides Y_2 and Z_2 are similar to those shown. [10].

B. Impact of the error of the phase difference measurement

There are strictly increasing dependences between the errors of determining the RT coordinates and the error of the phase difference measurement. When changing the error of the phase difference measurement $d\psi$ from 0° to 1°, resultant error of determining the RT coordinates ranges from 0 to 2000 km as it is shown in Fig. 5. [10].

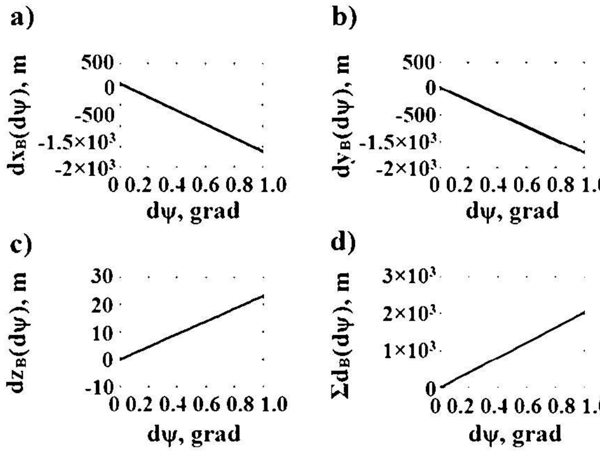

Fig. 5 – Dependences between the errors of determining the radio transmitter coordinates and the error of the phase difference measurement, $d\psi$:

a – Error of determining the radio transmitter coordinate x_B
b – Error of determining the radio transmitter coordinate y_B
c – Error of determining the radio transmitter coordinate z_B
d – Resultant error of determining the radio transmitter coordinates

Therefore, the method described above allows to determine the coordinates of the RT which is located outside the Earth's surface, that makes it possible to extend the applicability of the method based on the use of the VAA. However, based on the error study above, it is possible to draw a conclusion about the need to pay more attention to the implementation of the phase meter, since its error is the largest contributor to the errors of determining the RT coordinates.

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